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Dynamics and Mechanism of Cavitation Erosion on Perspex and Epoxy Resins Tested in a Rotating Disk Device

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DYNAMICS AND MECHANISM OF CAVITATION EROSION ON PERSPEX

AND EPOXY RESINS IN A ROTATING DISK DEVICE

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SUMMARY

The initiation, dynamics and mechanism of the cavitation erosion process on perspex and epoxy resin tested in a rotating disk device are described in some detail. The erosion always initiates at the area nearest to the center of rotation of the disk although erosion also starts at other areas as exposure increases. Most of the material loss appear to occur from the networks of cracks due to their interaction.

INTRODUCTION

In spite of improved designs of various modern machinery, the problem of cavitation and its detrimental effects appear to have increased. This may be due partly to increasing speed of the particular components of the machinery with reduced sizes. In order to protect the base metallic materials during erosive conditions, several plastic and elastomeric materials as well as polymers have been used as coatings and overlays.

Many studies (e.g. refs. 1 to 3) have been conducted on nonmetallic materials using rotating disk (with holes as inducers) and magnetostriction devices. However, there is no systematic investigation pertaining to the dyanamics, mechanism, growth and extent of erosion on nonmetallic materials with respect to time in a test facility which simulates field devices. It has been reported in the literature (ref. 4) that epoxy and polymer concretes are highly resistant to cavitation erosion than ordinary concretes.

In an earlier paper (ref. 5), the authors mentioned briefly the general dynamics of cavitation erosion on nonmetallic materials while studying the same in detail on metallic materials in a rotating disk device.

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This paper presents the specifics of the dynamics, material removal processes and secondary erosion of perspex with respect to time. The study also attempts to understand the erosion resistance mechanism of the epoxy resin.

TEST FACILITY AND EXPERIMENTAL CONDITIONS

A rotating disk device was used for conducting the experiments. The details of the test facility and disk were reported earlier (ref. 5). The details pertaining to the present study are as follows: materials - perspex and epoxy resins; test liquid - water; temperature - 32 ± 2^{0} C; velocity - 35 to 37.3 m/s; pressure - 0.15 MPa (abs); diameter and height of the cylindrical brass cavitation inducer - 25.4 and 3 mm respectively; and diameter and thickness of specimens - 63.5 and 3 mm respectively. Table 1 presents material properties of perspex and epoxy resins.

EROSION CHARACTERISTICS

The erosion - time curves for perspex and epoxy resin A are presented in figs. 1 and 2. Epoxy resin B specimens were breaking down in the rotating disk chamber as the erosion progressed. Table 2 presents incubation periods, peak rates of erosion on ersoion rate-time curves and the times to attain them. Except for velocity = 36.6 m/s in the case of perspex, the magnitude of erosion decreases as velocity decreases, i.e., with increased velocity the erosion resistance decreases for both materials. Although epoxy resin A is less resistant than perspex during the initial phases of erosion, it becomes more resistant as erosion progresses. It may be surmised that higher tensile strength and yield strength of epoxy resin A may be contributing to its higher resistance at advanced stages of erosion. The shapes of erosion - time curves of perspex (fig. 1) are different from those of perspex tested in a magnetostriction apparatus (ref. 6). However, the present plots in some cases look similar to the ones on the same material tested in a flowing venturi (refs. 7 and 8), using water and mercury as test liquids.

DYNAMICS OF EROSION PROCESS

A set of photographs of erosion patterns on the front and the rear sides of perspex specimen subject to 15 to 480 minutes exposure times at p = 0.15 MPa (abs) and V = 36.6 m/s is shown in fig. 3. CR in the figure indicates the direction of the center of rotation, top arrow shows the direction of the location of the cavitation inducer and the horizontal line is a reference line drawn from the CR to the point of first erosion initiation. The photographic details pertaining to perspex only are presented since the dynamics of erosion mechanism and material removal are almost similar for both perspex and epoxy resin A. A slight deviation was observed in the patterns of eroded areas of the three specimens tested under identical conditions, similar to those observed with aluminum (ref. 5). A symmetric and/or uniform pattern of erosion observed on perspex specimens tested in a constricted tube device (ref. 9) or a magnetostriction apparatus (refs. 3 and 6) was not observed in the present investigation (fig. 3) or in earlier reports (refs. 1 and 2) in which several nonmetallic materials were tested in a rotating disk device. A comparison of figures 1 and 3 clearly demonstrates the contribution of different areas (of erosion) on cumulative ero-

sion with respect to time. All erosion rate-time curves indicate a sharp peak rate of erosion (table 2).

Initiation of Erosion

Observation of perspex and epoxy resin A specimens at different velocities indicated that the erosion started first at the portion nearest to the CR (location N, Fig. 3), as observed in aluminum also (ref. 5). As the time increased, erosion also started at the portion away from the CR (location M, fig. 3). However, the initiation point for the location at M is more towards the cavitation inducer. It is observed that the erosion area at N increased faster than at M. However, the situation seems to be vice versa for metal- lic materials. The depth of erosion is maximum at location N than at location M. The erosion areas at M and N never equalized. In all the specimens, a hole was pierced by cavitation erosion through the 3 mm thick specimen at the location N although there was no evidence of erosion at location M. In due course the eroded pit at N initiated secondary erosion (SE in fig. 3(g)) away from the main pit and seemed to be more symmetric on perspex (figs. 3(g) and (h)) and epoxy resin A than on aluminum (ref. 5).

Area and Growth of Erosion

The photographs in fig. 3 clearly indicate the changes in the area and growth of erosion with respect to time and the reference line (both upstream and downstream at locations M and N). The area of erosion at N moved both toward upstream direction and away from the CR as observed with aluminum (ref. 5), the only difference being a very slow growth rate on plastic materials. Once the secondary erosion merges with the main pit, the growth rate of erosion is towards downstream. On the other hand, the area of erosion at M gradually moved both upstream and downstream to coalesce with the area of erosion at N. The growth rate is slower in the upstream direction.

THE EROSION MICHANISM AND MATERIAL REMOVAL PROCESS

The photographs of different areas taken at different time intervals on perspex tested at $p = 0.15$ MPa (abs) and $V = 37.3$ m/s are shown in fig. 4. Although the impact sequence could not be traced precisely due to the interaction of a large number of impacts by microjets and/or shockwaves, perspex clearly shows crack initiation, growth and removal of material due to its good transparency characteristics. The micro-crack network and density predominate during the incubation period (fig. 4(a)), during which no measurable weight loss is obtained (table 2). The micro-cracks develop into macro-cracks in some cases and travel in all directions. On the other hand, small cracks are initiated along the macro-cracks of 5-15 μm size. As erosion progresses the micro- and macro-crack densities increase (fig. 4(b)). The subsurface crack propagation and resulting damage, not seen in Fig. 4(a), is very clear in figs. 4(b) and (c) along with crack growth into the material. Small and large crevices are formed at the sites of intersecting cracks. The intersecting cracks initiate most of the material fracture and removal. The pits contain a majority of irregular shapes on a microscopic scale (fig. 4), although triangular shapes predominate as crevices and pits (cavities) progress. The conchoidal fractures predominate at cavities (figs. 4(a), (d), (e), and (f)) and crevices supporting a

brittle type failure. The fractured surfaces are smooth which further indicate brittle fracture. The combination of strain associated with extensive surface fractures may be responsible for the brittle type erosion behavior of perspex and epoxy resin A. The repeated transient stresses on the liquid trapped in cracks due to subsequent microjet impacts may be responsible for this process. This mechanism under favorable conditions may enhance the crack propagation and interaction removing large pieces which result in quick material removal. Scanning electron micrographs showed that crevices and pits (cavities) contain many irregular shaped dislodging particles inside . This supports the view that crevices are shattered during the erosion process. Also the material removed seems to be like a thin layered structure. Further studies are however necessary to understand more about this possible mechanism and to gather more evidence for characterization.

The "scabbing effect" (ref. 10) observed for liquid impingement erosion tests on perspex is also observed in the present investigations (fig. 3). The initial undamaged areas around damaged surfaces are believed to be due mainly to compression waves induced by microjets. However, the wave of tension reflected from the back of the specimen may possibly induce failure of material locally. The shear induced by radial outflow of the microjets is responsible for increased damage and erosion on the surfaces. The increased number and dimensions of pits and/or crevices accelerate the erosion process. The interaction of cracks also result in the acceleration of erosion at advanced stages.

Unlike in glasses, the crack propagation never reaches the other end, except at advanced stages of erosion (fig. 3(h)). It is believed that the viscoelastic loss process may be involved during the initial phases of crack initiation and propagation. A comparison of the erosion progress in the present study with similar ones reported by several other investigators (refs. 10 to 14) in case of drop impact indicates that there is a lot of similarity in the mechanism of erosion, although the interaction and dynamics of erosion processes are different.

OPTICAL DEGRADATION

In the eroded areas at M and N, the reduction of transparency (optical degradation or transmittance) of the perspex specimen is obvious as erosion progresses with time (fig. 3). The optical degradation on the rear side appears to be more than on the front side. This may be attributed to the increased crack networks and random crack front travel in this material under severe cavitation erosion conditions. A detailed study of the loss of transmittance on either side of a transparent material is necessary from a practical point of view to choose a proper material in erosion environments. Since there are many similarities between erosion by cavitation and liquid jet impingement, this information is more specific for the latter type of erosion and for the choice of suitable materials for the windows and canopies during all weather operations (dust, rain, and storm environments) and for tactical aircraft.

CONCLUSIONS

1. On perspex, erosion starts first at the location nearest to the center of rotation (CR). As the exposure increases, the erosion also

initiates at the location away from the CR. The secondary erosion (induced by an eroded pit) starts away from the main pit and later moves upstream and merges with the main pit. The growth of erosion is entirely different at each of the two erosion locations N and M (fig. 3).

2. In general, micro-crack density increases towards the end of the incubation period transforming into macro-cracks in a majority of cases. Material particles are believed to be removed from the networks of cracks due to their interaction. The crack propagation into the material, crevices and pits (cavities) are clear at an advanced stage of erosion.

3. The loss of transmittance (optical degradation) is more on the rear side of the specimen than on the front side.

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TABLE 1. - MECHANICAL AND OTHER PROPERTIES OF PLASTIC MATERIALS

Material	Density, kg/m^3	Tensile strength,[a] MPa	Yield strength,[a] MPa	Elastic modulus,[a] GPa	Elongation,[b] %	Reduction in area,[b] %	Ultimate resilience,[c] MN/m^2
Perspex	1.22×10^3	70	38	2.1	2-10	0.0	0.12
Epoxy resin A	1.43	98	56	3.3	2-6	0.0	1.46
Epoxy resin B	1.40	84	49	3.3	2-6	0.0	1.07

[a]A. J. Durelli and W. F. Riley, "Introduction to Photomechanics," Prentice-Hall, Inc., Eaglewood Cliffs, New Jersey, 1965.
[b]R. E. Bolz and G. L. Tuve, "Handbook of Tables for Applied Engineering Science," The Chemical Rubber Co., Cleveland, Ohio, 1970, pp. 105-115.
[c]Ultimate resilience = $(\text{tensile strength})^2/(2 \times \text{elastic modulus})$.
Note: For epoxy resins A and B the resin used was araldite HY-230 supplied by Ciba and hardners were phthalic anhydrate and amine, respectively.

TABLE 2. - INCUBATION PERIODS OF PLASTIC MATERIALS TESTED

IN A ROTATING DISK DEVICE AT 0.15 MPa (abs) PRESSURE

Material	Velocity, m/s	Incubation period,[a] minutes	Peak rate on instantaneous erosion rate-time curve, mm^3/hr	Time to attain this peak, minutes
Perspex	37.3	4.0	247	30
	36.6	3.5	432	30
	35.8	8.0	72	128
	35.0	17.0	85	128
Epoxy resin A	37.3	2.6	377	7.5
	36.6	5.0	154	7.5
	35.8	14.5	234	7.5
	35.0	13.0	88	7.5
Epoxy resin B	37.3	14.0	---	---
	36.6	-----	---	---
	35.8	45.0	---	---
	35.0	60.0	---	---

[a]Some investigators define incubation period as the no weight loss period. On the other hand, other investigators define it as the intercept on the time axis obtained by extending the straight line portion of the cumulative erosion-time curve. In the present investigations the former definition is used.

Note: Three specimens were tested under identical conditions. Epoxy resin B specimens were breaking down in the rotating disk chamber each time the erosion progressed.

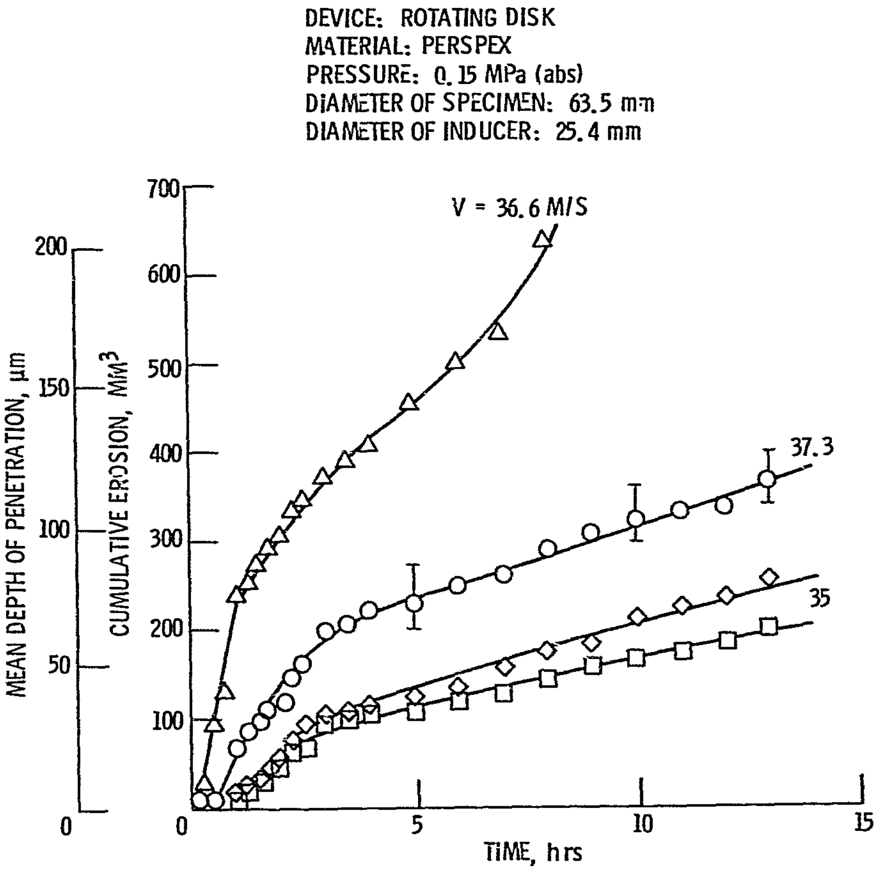

Figure 1. - Erosion - time curves of perspex.

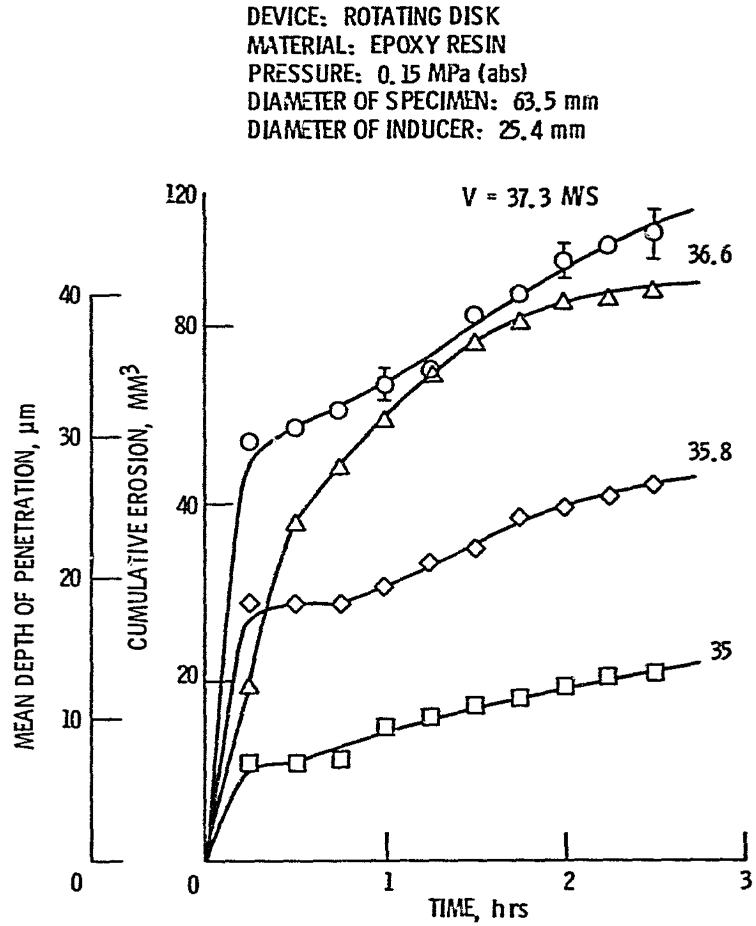

Figure 2. - Erosion time curves of epoxy resin.

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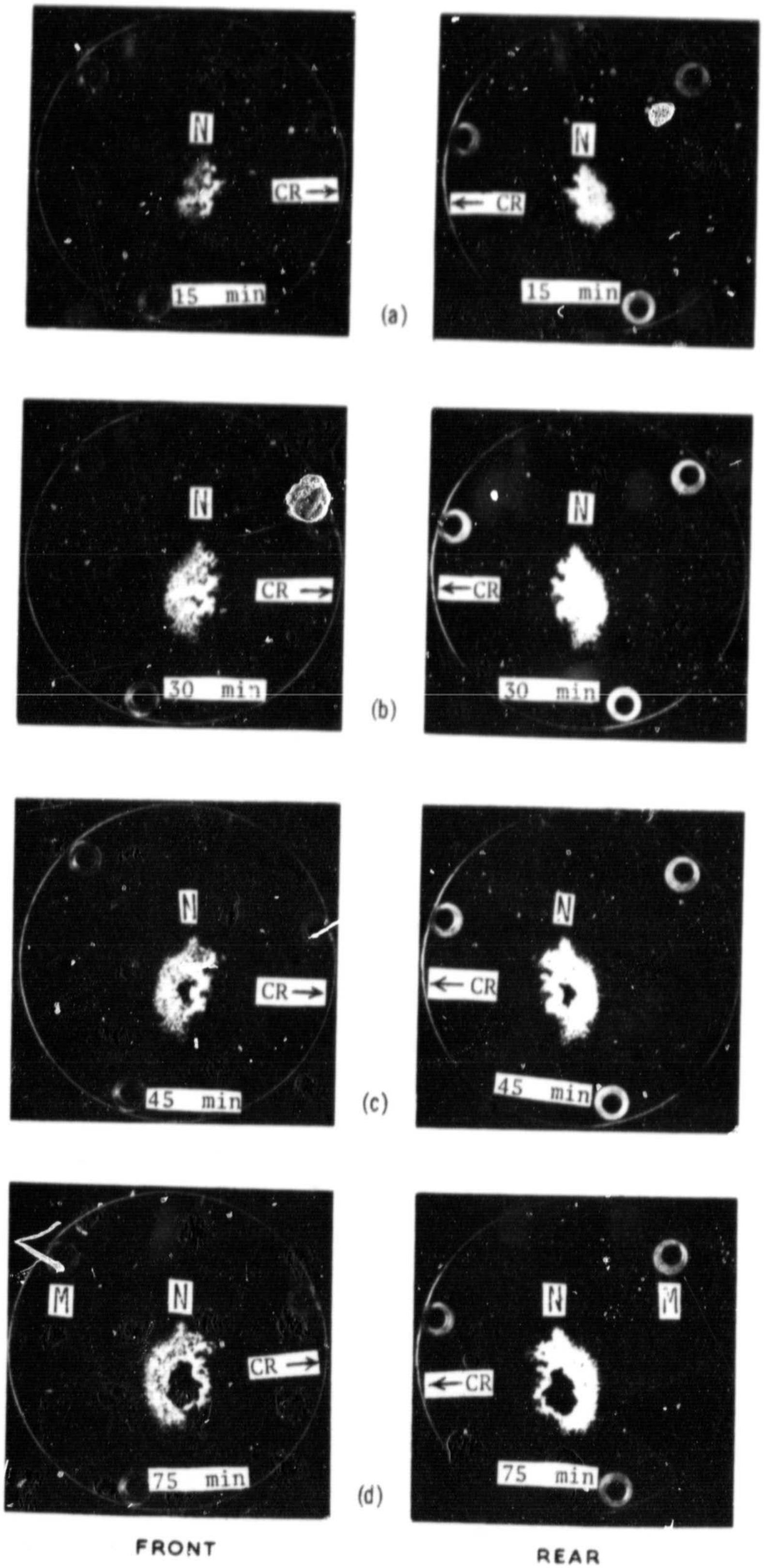

Figure 3. - Dynamics and growth of erosion on the front and rear side of perspex specimen (continued).

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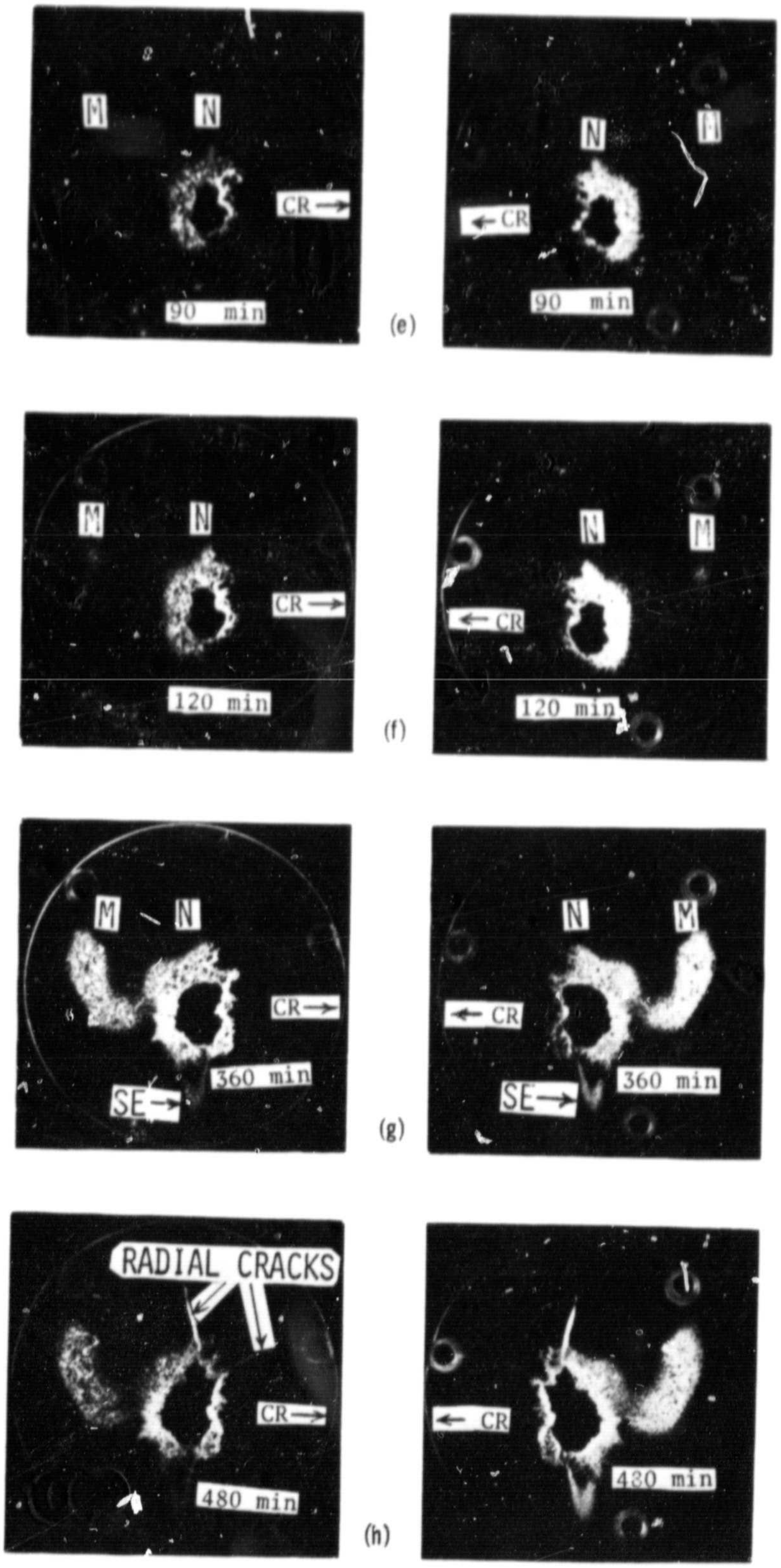

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Figure 3. - Concluded.

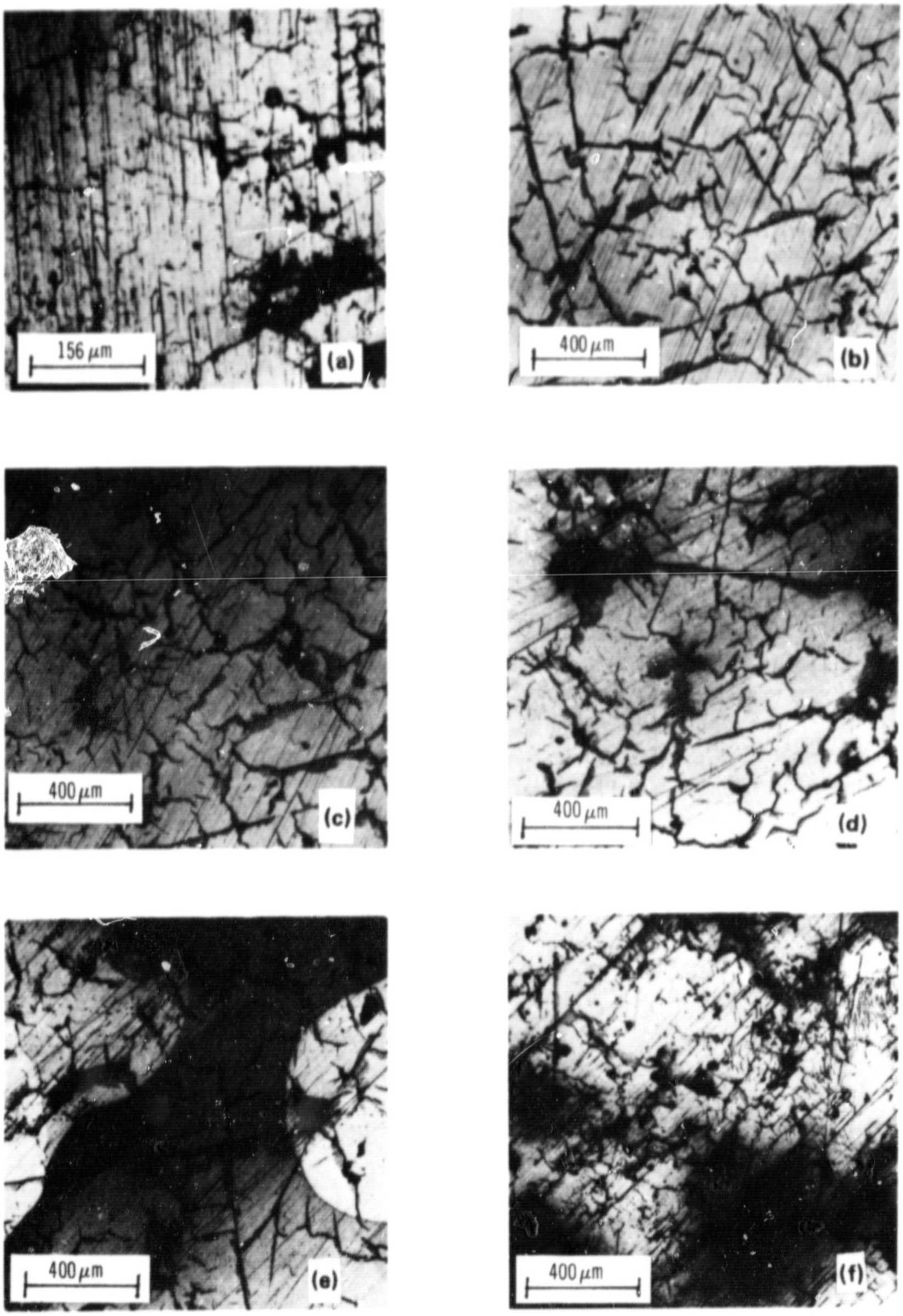

Figure 4. - Photographs of damage pattern on perspex specimen surface. (a) 75 min, (b) 240 min (growth of cracks into the material), (c) 255 min (material removal from crack intersection), (d) 285 min, (e) 315 min, (f) 435 min (heavily damaged and eroded area).